Monitoring surface soil moisture and freeze-thaw state with the high-resolution radar of the Soil Moisture Active/Passive (SMAP) mission

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Abstract— **An approach is described for retrieving surface soil moisture and freeze/thaw state using 3-km resolution L-band radar data of the planned Soil Moisture Active and Passive (SMAP) mission. SMAP radar backscatter coefficients are simulated using radar scattering models and land surface hydrology model output generated over the contiguous United States (CONUS). A Monte-Carlo simulation is performed to assess the error budget of the soil moisture retrievals in the presence of radar measurement error and error in surface roughness. The estimated soil moisture retrieval accuracy is better than 0.06 cm^3/cm^3 for vegetation water content less than 1.2 kg/m^2 and soil moisture in the range of 0 to 0.3 cm^3/cm^3. The retrieval performance improves if radar speckle is reduced by additional observations (e.g., including both fore- and aft-scan data). It is currently assumed that the surface roughness is known with 10% error, but a time-series method is under development to estimate the roughness. The surface freeze/thaw state retrieval is simulated using a surface hydrology process model forced with climatology. The simulation illustrates a SMAP daily composite freeze/thaw product derived using a time-series algorithm applied to the SMAP high-resolution radar data.**

I. INTRODUCTION

The Soil Moisture Active and Passive (SMAP) mission, scheduled for launch in 2014, will offer simultaneous measurements with a synthetic aperture radar (SAR) and a radiometer operating at 1.26 and 1.41 GHz (L-band) respectively. SMAP will provide global land surface measurements of soil moisture and freeze/thaw state. The soil moisture measurements will be used to enhance understanding of processes that link the water and energy cycles and their applications. The freeze/thaw measurements are aimed at quantifying net carbon flux in boreal landscapes. These data will help extend the capabilities of weather and climate prediction, flood forecasts, drought monitoring, and agricultural prediction.

The SMAP L-band radar measures HH, HV, and VV polarized backscatter (σ_0). The offset parabolic mesh reflector antenna scans conically about the nadir axis such that there is a fixed 40-degree earth-incidence angle across the 1000-km swath. At the edge of the swath, the radar samples have a single-look spatial resolution of 250 m in range and 400 m in azimuth after SAR processing. The azimuth resolution degrades towards the center of the swath. The σ_0 values are averaged (multi-looked) and posted at a 1 km grid spacing. The spatial resolution of the 1-km posted data ranges from 1 km to 3 km over the outer ~70% of the swath. The relative accuracy of the co-pol channels is designed to be less than 0.9 dB, which consists of speckle noise and other errors including calibration and radio frequency interference. The orbit is polar, sun-synchronous, with 680-km altitude and 8-day exact repeat. The wide swath provides global coverage on average every 3 days or less at the equator and every 2 days or less in the boreal regions poleward of 45°.

This paper describes forward simulations of SMAP radar observations and retrieval simulations of soil moisture and freeze/thaw state. The forward simulation is implemented on the SMAP Science Data System (SDS) Testbed over the contiguous U. S. (CONUS) domain. Future tests will be conducted over more extensive domains.

II. SOIL MOISTURE RETRIEVAL

SMAP plans to provide a 10-km resolution soil moisture product for hydrometeorology applications using an optimal algorithm combining the SMAP radar (3-km resolution) and radiometer (40-km resolution) observations. The desired accuracy of the 10-km soil moisture product is 0.04 cm^3/cm^3, which provides five or more levels of moisture discrimination between dry and saturated soil and allows estimation of surface fluxes to within the in situ observation error [1]. The accuracy target is relaxed to 0.06 cm^3/cm^3 for the radar-only retrieval at 3-km resolution, considering the challenge of radar soil moisture retrieval in the presence of roughness and vegetation. In this section, the feasibility of achieving the radar-only soil moisture retrieval accuracy is examined through the simulation of radar forward scattering and retrieval.

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14. ABSTRACT

An approach is described for retrieving surface soil moisture and freeze/thaw state using 3-km resolution L-band radar data of the planned Soil Moisture Active and Passive (SMAP) mission. SMAP radar backscatter coefficients are simulated using radar scattering models and land surface hydrology model output generated over the contiguous United States (CONUS). A Monte-Carlo simulation is performed to assess the error budget of the soil moisture retrievals in the presence of radar measurement error and error in surface roughness. The estimated soil moisture retrieval accuracy is better than 0.06 cm3/cm3 for vegetation water content less than 1.2 kg/m2 and soil moisture in the range of 0 to 0.3 cm3/cm3. The retrieval performance improves if radar speckle is reduced by additional observations (e.g., including both fore- and aft-scan data). It is currently assumed that the surface roughness is known with 10% error, but a timeseries method is under development to estimate the roughness. The surface freeze/thaw state retrieval is simulated using a surface hydrology process model forced with climatology. The simulation illustrates a SMAP daily composite freeze/thaw product derived using a time-series algorithm applied to the SMAP high-resolution radar data.

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A. *Forward scattering model*

Two models for radar forward scattering are described here to simulate σ_0. In general, the total σ_0 (σ_0^{total}) consists of a bare surface component (σ_0^s), a volume scattering component from the vegetation canopy (σ_0^v), and interaction between bare surface and volume (σ_0^{sv}):

$$\sigma_0^{total} = \sigma_0^s \exp(-2\tau\cos\theta) + \sigma_0^v + \sigma_0^{sv}, \qquad (1)$$

where τ is the vegetation opacity and θ is the local incidence angle. A simplified empirical model has been considered that incorporates the bare surface models of Dubois et al. [2] for co-pol and Oh et al. [3] for cross-pol, and the vegetation cloud model of Ulaby et al. ([4], Ch. 21.5) for the volume and interaction components. Hereafter this model will be referred to as the DOU model. The relationship between soil moisture and permittivity is defined by the dielectric model of Dobson et al. [5]. A second model considered uses the small perturbation model (SPM) for a bare surface ([6], Ch. 2) and a discrete scattering model (DSM) for vegetation scattering [7]. The dielectric model used in this case is from Hallikainen et al. [8]. This model will be referred to as the SPM/DSM. DSM computes scattering from individual scatterers using the infinite cylinder approximation, and double-bounce using the Kirchoff surface method. DSM is configured for a grass surface only at present.

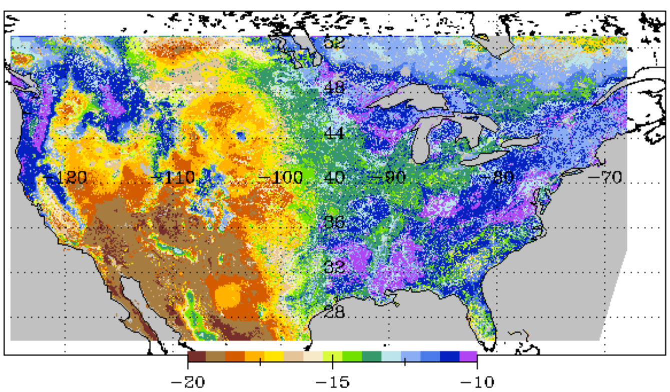

Figure 1. Simulated σ_{0HH} in dB for a composite of six simulated SMAP descending (AM) orbits using geophysical model data for June 2004.

B. *Forward simulation with land surface model output data*

Our present simulation covers the contiguous U. S. domain where there is ready availability of high-resolution (1 km) land surface model simulation data. The simulation is based on the DOU empirical radar backscatter model. Later, as more sophisticated models for different land surface classes become available those will be used. For the forward simulation, moisture and temperature fields were generated by the Noah land surface model [9] by Kumar et al. [10] at 1 km resolution and 6-hourly. Vegetation water content (VWC) was derived from MODIS NDVI data using a simple empirical relationship. Static fields of surface characteristics were derived from a MODIS based land surface classification, and surface texture data were obtained from the U. S. General Soil Map (STATSGO) at 1 km resolution.

An example of σ_0 is shown in **Figure 1** for the HH channel. Gaussian random noise with a magnitude of 0.9 dB (1-sigma) is multiplied to represent effective Kp noise that includes speckle (0.7 dB), relative calibration error (0.35 dB), and contamination from radio frequency interference (0.4 dB). This noise level was applied uniformly across all three polarimetric channels in an uncorrelated manner and represents a worst case (actual error is expected to be less than 0.9 dB). The backscatter $\sigma 0$ is large in the Pacific Northwest and Eastern U. S. where the denser vegetation significantly influences the scattering.

C. *Soil moisture retrieval*

The DOU model has deficiencies in representing the cross-pol vegetation volume scattering. Therefore, the retrieval simulation is studied instead using the SPM/DSM. The same radar model is used here for both the forward and retrieval processes. This allows study of the impacts of instrument and aggregation errors alone. As a parallel activity, the quality of the radar forward model will be examined by comparing with observational data and by model inter-comparisons. In the retrieval simulation the soil moisture (Mv_{rtr}) and vegetation water content (VWC_{rtr}) values are retrieved so as to minimize the distance (d) that is defined as:

$$d = \sum_{i=HH,VV,HV} w_i \left(\sigma_{0,i,fwd} - \sigma_{0,i,rtr}(Mv_{rtr}, VWC_{rtr}, ancillary)\right)^2, \quad (2)$$

where $\sigma_{0,fwd}$ are the SMAP "observations" (forward-simulated backscatter). The estimated backscatter, $\sigma_{0,rtr}$, is evaluated using Mv_{rtr}, VWC_{rtr}, and the ancillary fields. The weight, *w*, is currently set to 1 for all three input channels. During the minimization, dB units are used for σ_0, noting that σ_0 in dB has a near-linear relationship with permittivity and in turn with soil moisture (at least over the lower soil moisture range). The 3-channel inputs (HH, VV, and HV) determine two unknowns (Mv and VWC). The two unknown parameters are chosen for the retrieval since this choice resulted in better Mv retrieval performance than other choices. Surface roughness is assumed known within some assigned uncertainty.

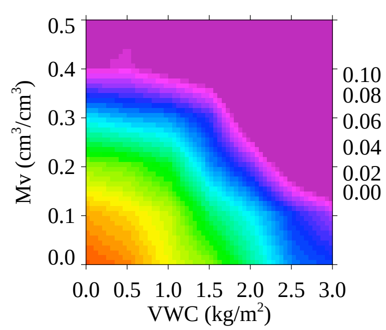

Figure 2. Monte-Carlo simulation of soil moisture retrieval error for VWC up to 3 kg/m^2, performed using the SPM/DSM

model. The purple color includes errors greater than 0.1 cm^3/cm^3.

For the first part of the study, a Monte-Carlo simulation was performed to understand the behavior of the soil moisture retrieval using Eq. 2. Soil moisture is varied from 0 to 0.5 cm^3/cm^3 with increments of 0.1. VWC is varied from 0 to 5 kg/m^2 in increments of 0.5. The surface roughness value is set to 0.3 in terms of *ks* (*k* is the wave number and *s* is the rms height). The result is interpolated onto a finer grid for moisture and VWC to generate **Figure 2**. Two random variables in the simulation are the Kp noise of 0.9 dB (that is, multiplicative noise of 22% magnitude) and a 5% uncertainty in the knowledge of surface roughness. For a bare surface (VWC = 0), the retrieval error ranges from 0.02 to 0.06 over the moisture range of 0 to 0.3. This result is consistent with that of Dubois et al. [2], although direct comparison is difficult due to differences in the retrieval approaches. In general the retrieval error increases with VWC. The soil moisture signal is attenuated by the vegetation layer, which makes the retrieval more sensitive to Kp noise and roughness uncertainty. The retrieval error also shows a signal-dependent characteristic with larger error occurring at higher moisture, consistent with the nonlinear dependence of backscatter on soil moisture.

In the second part of the study, retrievals were simulated using the CONUS land surface dataset described earlier. 1500 samples within one SMAP orbit covering Arizona to Michigan were randomly selected and retrievals were performed using the SPM/DSM. Compared with the Monte-Carlo simulation this experiment employs more realistic inputs of soil moisture, VWC, and surface roughness and their geophysical correlations. With Kp noise of 0.9 dB, and 5% error in roughness knowledge, 0.06 cm^3/cm^3 soil moisture retrieval accuracy is achievable for VWC up to 1.2 kg/m^2 (**Figure 3**). Speckle is a major contributor to the Kp noise, therefore Kp can be reduced significantly by increasing the number of looks. The 0.9 dB specification is an upper limit representing the maximum anticipated instrument error at 3-km resolution, computed using only the fore-look portion of the 360° antenna scan. By adding the aft look (doubling the number of samples), the Kp noise is reduced to 0.7 dB. In this case, the VWC range that allows the 0.06 cm^3/cm^3 retrieval accuracy increases to 1.7 kg/m^3. At the outer edge of the swath, with fore- and aft- looks, the Kp noise is 0.6 dB. In this scenario, the VWC up to 2.2 kg/m^2 is permissible for adequate retrieval.

The above analysis has the following caveats. The soil surface roughness is assumed known to within 5% error. The accuracy of the roughness knowledge affects the retrieval performance in low-vegetation cases where the surface scattering dominates over the scattering and attenuation by the vegetation. When the retrieval is simulated with 10% roughness error, the retrieval errors in **Figure 3** increase by 0.01 cm^3/cm^3 for the bare surface and by 0.005 cm^3/cm^3 for 2 kg/m^2 VWC, compared with those of the 5% case. Uncertainties in the radar model have not been accounted for. One approach to assess the model error is to use different radar models in the forward and inverse processing.

The retrieval analysis presented above is based on a single time 'snapshot' retrieval approach. This approach is limited by vegetation as the soil moisture signal is attenuated and scattered by a significant vegetation canopy. An alternative is to estimate relative change in soil moisture, as opposed to absolute soil moisture, through temporal analysis of backscatter time series, assuming that vegetation effects do not vary significantly during the time interval of interest [11]. A study of such time-series approaches is under way.

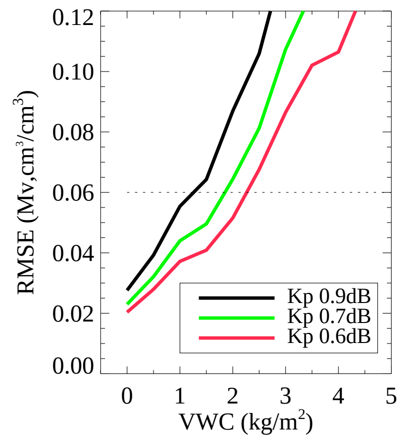

Figure 3. Soil moisture retrieval error simulated using SPM/DSM over one SMAP pass within the continental U. S. Different Kp noise levels and 5% error in knowledge of the surface roughness were introduced during the retrievals. The unevenness of the retrieval curve (e.g., at 1 kg/m^3) is mostly due to the unevenness in the geographic representation of the input parameter fields.

III. FREEZE/THAW CLASSIFICATION

The SMAP mission baseline requirements call for SMAP to provide measurements of surface freeze/thaw state for areas north of 45 degrees north latitude with a classification accuracy of 80% at 3 km spatial resolution and 2-day average repeat intervals. SMAP will meet these requirements, providing daily composite maps of land surface freeze/thaw state based on high resolution (1-3 km) radar backscatter time series. Freeze/thaw state will be provide as a binary state (i.e. frozen or thawed) as a global product with the baseline freeze/thaw requirements satisfied for latitudes north of 45 degrees North.

A. *Freeze/Thaw retrieval algorithm*

The retrieval of landscape freeze/thaw state relies on analysis of time series radar backscatter for identification of temporal changes in backscatter associated with differences in the aggregate landscape dielectric constant that occur as the landscape transitions between predominantly frozen and non-frozen conditions. This technique assumes that the large changes in dielectric constant occurring between frozen and non-frozen conditions dominate the corresponding backscatter temporal dynamics. This is generally valid during periods of seasonal freeze/thaw transitions for most areas of the cryosphere.

The SMAP baseline freeze/thaw state classification algorithm compares the time sequence of radar backscatter relative to backscatter acquired during a seasonal reference state or states [12]. This seasonal threshold algorithm may be expressed through definition of a seasonal scale factor:

$$\Delta(t) = \frac{\sigma(t) - \sigma_{fr}}{\sigma_{th} - \sigma_{fr}}, \tag{3}$$

where $\sigma(t)$ is the backscater measured at time t, and σ_{fr} and σ_{th} are backscatter values corresponding to landscape frozen and thawed reference staes, respectively. A threshold value T is defined such that $\Delta(t) > T$ and $\Delta(t) \leq T$ define the thawed and frozen landcscpae state, respectively. The selection of T may be optimized for various land cover conditions and sensor configurations.

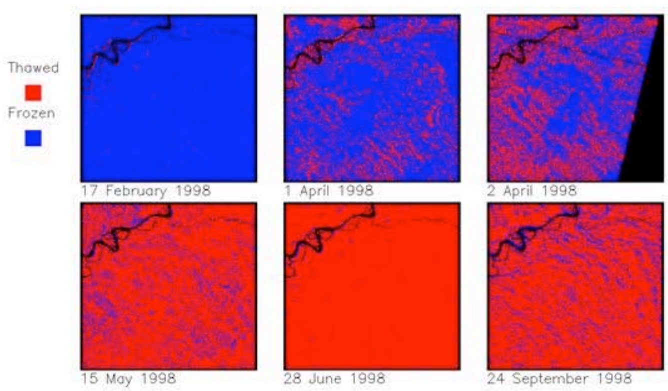

Figure 4. An example of time series landscape freeze/thaw state classification derived using a temporal sequence of L-band SAR images acquired by JERS-1 in 1998 for a region of the Tanana River Floodplain near Fairbanks, Alaska. Derived at 100m resolution, these products cover the time period of the dominant seasonal thaw transition (between 1 April and 15 May) and the initial stages of seasonal freeze (24 September).

An example of freeze/thaw state derived from multi-temporal JERS-1 SAR images for a region of the Tanana River Floodplain near Fairbanks, Alaska is shown in Figure 4. In this example, T = 0.5. Algorithm performance has been validated using *in situ* data sets from biophysical monitoring stations [1, 13]. Assement of freeze-thaw algorithm performance using a variaety of microwave sensors has shown similar spatial-temporal patterns, with 72-93 % mean annual classification accuracy relative to NCDC stations [14]. These 10-meter resolution products cover the dominant seasonal springtime thaw transition and the initial stage of autumn freeze. SMAP will support generation of similar products at 1-3 km spatial resolution with significantly improved temporal fidelity (2 days).

B. *Retrieval product demonstration*

Figure 5 shows an illustration of the SMAP freeze/thaw product generated using a land surface hydrologic modeling framework. This example was derived through application of the Pan-Arctic Water Balance Model (PWBM [15]) forced with time-varying climate data (air temperature and precipitation) derived from the NCEP/NCAR reanalysis project. The PWBM simulations are daily and are provided on a Northern Hemisphere Equal-Area Scalable Grid (EASE-Grid). Results shown are for modelled soil temperature corresponding to the layer from 0 to 5 cm.

IV. SUMMARY

Approaches and simulation results for retrieving surface soil moisture and freeze/thaw state from SMAP measurements have been discussed in this paper. Soil moisture retrievals were examined using the small perturbation and discrete scattering models (SPM/DSM) for radar scattering at L-band, and land surface model simulation fields. Enhanced radar scattering models and time-series approaches will be implemented and reported in the near future. A demonstration of the freeze-thaw state product has been developed using an integrated land surface hydrologic modeling scheme. The freeze/thaw product for SMAP will be derived using a time series analysis of the high resolution radar backscatter.

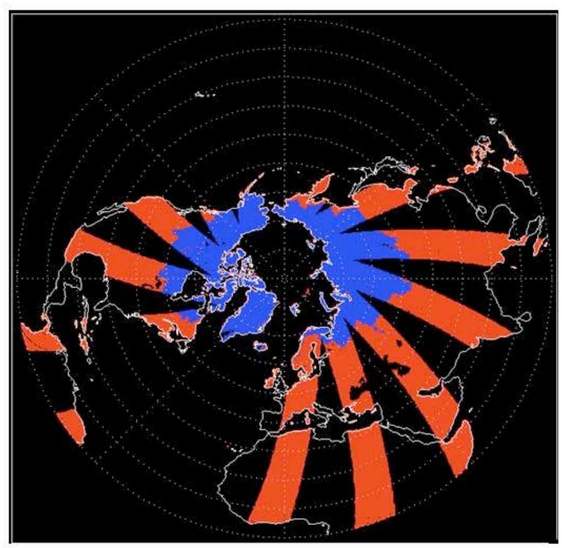

Figure 5. A demonstration of the construct of the SMAP daily Level 3 Freeze/Thaw product derived using a land surface hydrology model driven by NCEP/NCAR reanalysis data to simulate freeze/thaw state in the terrestrial pan-Arctic basin, and assuming thawed conditions outside that basin. Blue and red denote frozen and thawed regions, respectively.

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